GEOLOGICA SAXONICA
Journal of Central European Geology

59: 65–73
12 Sept 2013

SENCKENBERG

Morphology of zircon crystal grains in sediments – characteristics, classifications, definitions

Morphologie von Zirkonen in Sedimenten – Merkmale, Klassifikationen, Definitionen

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Revision accepted 15 May 2013.
Published online at www.senckenberg.de/geologica-saxonica on 10 September 2013.

Abstract

Morphology of zircon crystal grains, especially in sediments, was investigated only by few authors but may indicate distance and medium of transport. If this assumption was proven, an additional tool for common provenance analyses of zircons could be created. Based on already established results for other minerals and new investigations, especially for zircons, the particular parameters have to be defined and classified. Therefore, this work is thought to be a suggestion for further studies.

Kurzfassung

Die Morphologie von Zirkonkristallen, insbesondere in Sedimenten, wurde bisher nur von relativ wenigen Autoren untersucht. Dennoch können aus den morphologischen Merkmalen möglicherweise Rückschlüsse bezüglich des zurückgelegten Transportwegs und -mediums gezogen werden. Damit eröffnet sich die Möglichkeit ein zusätzliches Werkzeug in Ergänzung zu den derzeit angewandten Methoden der Provenienzanalyse an Zirkonen zu entwickeln. Die Zirkonkristalle werden, basierend auf für andere Minerale bereits etablierten Resultaten sowie neuen, speziell Zirkone betreffenden Ergebnissen, definiert und klassifiziert. Die vorliegende Arbeit hat das Ziel, als Anwendungsvorschlag für künftige Arbeiten auf diesem Gebiet zu fungieren.

1. Introduction

Previous investigations revealed a widespread variety in attributes of zircon crystal morphology (e.g. Freise 1931, List 1966, Saxena 1966, Voggenreiter 1986, Finger & Haunschmid 1988, Tejan-Kella et al. 1991, Sinha et al. 1992, Balan et al. 2001, Moral Cardona et al 2005). All of them contained either aspects of roundness or crystal habit as well as surface characteristics but did not mention a combination of these different properties. Classifications which are consistent and useable as a guideline for further research projects are scarcely available. Exceptions are zircon typology and internal texture, which are well described and used in literature (e.g. Pupin 1980, Vavra 1990, 1994, Vavra et al. 1996, Corfu et al. 2003). Hence, the latter ones will not be discussed in this work.

2. Methods

During this study, zircon grains from different samples of recent sands from various environments (Tab. 1) were analysed. After drying 1 to 2 kg of the fresh sample at room temperature, the material was sieved for the fraction from smaller than 2 mm. Heavy mineral separation was achieved from this fraction using LST (lithium heteropolytungstate in water) prior to magnetic separation in the Frantz isomagnetic separator. Final selection of zircon grains was achieved by hand-picking under a binocular microscope (ZEISS Stemi 2000-C). Afterwards, zircons of all sizes and morphological types were selected and put on a tape. In order to get pictures of zircon grains with a very high resolution and magnification, a scanning electron microscope (SEM) ZEISS Evo 50 was used in the back scattered electron (BSE) mode. Imaging in the cathodoluminescence (CL) mode was performed via connection with a CL-detector (HONOLD®) operating with a spot size of 550 nm at 20 kV. In consideration of statistical reasons, it is advisable to investigate about 300 zircon grains per sample (Fedo et al. 2003).

3. Classification and definition of characteristics

An application-oriented classification of the investigated characteristics (roundness, elongation, surface characteristics) is necessary for further studies including this topic. Therefore, the suggested classes have to be defined within limits, which allow to draw a clear distinction from each other.

3.1. Roundness

Following the definition of Murawsky & Meyer (2010), roundness is the smoothening of crystal edges caused by abrasion. It is supposed to be the main indicator determining the energetic dimension affecting zircon grains during the entire transport process (Köster 1964, Dietz 1973). Hence, it is a parameter for the already realised distance of transport. Additionally, there is the necessity to consider the problem of roundness caused by physicochemical processes such as recrystallisation (Mager 1981, Deer et al. 1997, Tichomirowa 2003), corrosion effects from the transporting magmas (Hollis & Sutherland 1985), and pre-rounded grains as detrital components especially in S-Type granites (Tichomirowa et al. 2001, Roger et al. 2004). The mentioned processes have only slight influence on the results, because the reported percentage of already rounded grains is generally low (Hoskin & Black 2000, Tichomirowa 2001, Tichomirowa et al. 2001, Tikhomirova 2002).

Citing only few of the many possible classifications of different authors like Cailleux (1945, 1947a, 1947b, 1952), Cox (1927), von Szadecky-Kardoss (1933), Stow (2008), Wadell (1935), Wentworth (1933) etc., it is obvious that, due to the multitude of authors, there is large heterogeneity and no agreement concerning definition or classification of roundness. Paying attention to the necessity of a well-defined and well-divided scale, the five-staged classification after Schneiderhöhn (1954) was modified into a system of ten classes of roundness (Fig. 1). The feasibility to classify the grains by the meaning of Pupin (1980) is an additional tool for determination. Resulting advantages are smooth curves within a decimal scale, which are quite stable against outlier effects.

The ten classes of roundness are defined as:

1 Completely unrounded: The grain shows very sharp edges without any exception, the single crystal faces are distinguishable without problems; classification *sensu* Pupin (1980) is possible.

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2 Almost completely unrounded: Some edges of the grain are slightly rounded, the single crystal faces are distinguishable without problems; classification *sensu* Pupin (1980) is possible.

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3 Very poorly rounded: Most edges and angles are slightly rounded, the single crystal faces are distinguishable without problems; classification *sensu* Pupin (1980) is possible.

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4 Poorly rounded: Almost all edges and angles are rounded, only few angles show lesser rounding in the contour of the whole grain. Nevertheless, the single crystal faces are distinguishable without problems and a classification *sensu* Pupin (1980) is possible.

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5 Fairly rounded: All edges and angles are rounded. Partially, some crystal faces show a smooth transition to the neighbouring ones. Nevertheless, the single crystal faces are distinguishable without problems and a classification *sensu* Pupin (1980) is possible.

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6 Rounded: In consequence of progressive rounding, all edges and angles are clearly rounded. All crystal fac-

Table 1. Sample localities of the investigated sediments (latitude and longitude given in coordinates of WGS84).

Tabelle 1. Probenahmepunkte der untersuchten Sedimente (Breiten- und Längenangaben in Koordinaten des WGS84).

Sample	Latitude	Longitude
E1, Elbe River, Bad Schandau, Germany, fluvial sand	N 50° 54′ 45.9″	E 14° 10′ 06.5″
E0, Elbe River, Dresden, Germany, fluvial sand	N 51° 03′ 20.3″	E 13° 44′ 22.0″
E3, Elbe River, Coswig, Germany, fluvial sand	N 51° 06′ 54.2″	E 13° 34′ 06.7″
E5, Elbe River, Groß Schönebeck, Germany, fluvial sand	N 52° 01′ 41.0″	E 11° 46′ 16.6″
E7, Elbe River, Jasebeck, Germany, fluvial sand	N 53° 09′ 49.0″	E 11° 09′ 21.6″
Zr-A, Binnenelbe near Otterndorf, Germany, fluvio-marine sand	N 53° 51′16.4″	E 8° 58′ 1.9″
Zr-D, Außenelbe, Germany, fluvio-marine sand	N 53° 59′8.4″	E 8° 35′ 25.4″
Zr-E, German Bight, Germany, marine sand	N 53° 59′20.8″	E 8° 17′ 19.8″
Zr-J, North Sea, Germany, marine sand	N 54° 15′44.0″	E 7° 32′28.4″
S1, beach near Ückeritz, Germany, beach sand	N 54° 00′ 56.1″	E 14° 04′ 19.2″
NAM 23, dune near Maltahöhe, Namibia, aeolian sand	S 24° 53′ 58.4″	E 16° 53′ 33.7″
NAM-O-23, Cunene River west of Ruacana Namibia, fluvial sand	S 17° 25′ 50.6″	E 14° 07′ 09.9″
NAM-O-25, Okavango River near Kitwiti, Namibia, fluvial sand	S 17° 23′ 27.9′	E 18° 25′ 14.9′ ′
NAM-O-32, Okavango River near Divundu, Namibia, fluvial sand	S 18° 06′ 22.2′ ′	E 21° 37′ 01.8′ ′
NAM-O-31, Kwando River near Chaoi Village, Namibia, fluvial sand	S 17° 51′ 19.9′ ′	E 23° 21′ 41.6′ ′
NAM-O-30, Zambezi River near Katima Mulilo, Namibia, fluvial sand	S 17° 29′ 35.4′ ′	E 24° 16′ 11.3′ ′
CHN8, dune near Dunhuang, China, aeolian sand	N 40° 04′ 25.1″	E 94° 40′ 32.7″

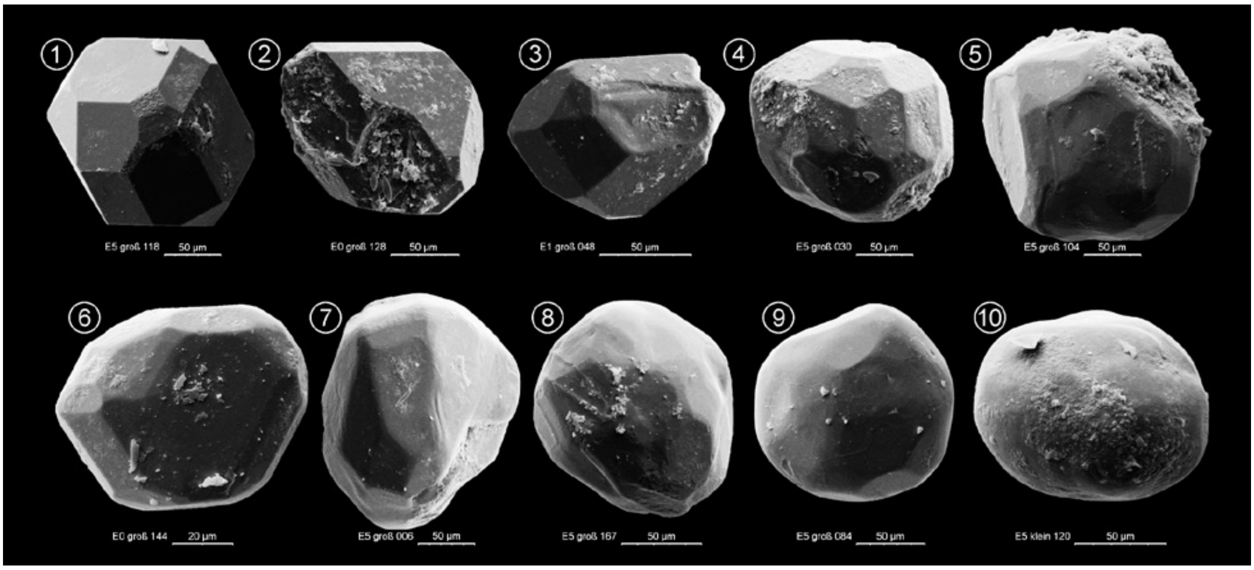

Fig. 1. One zircon grain exemplifying each of the ten classes of roundness (**1** to **10**, scale bar: 50 µm).

Abb. 1. Ein beispielhaftes Zirkonkorn aus jeder der zehn Klassen der Rundheit (**1** bis **10**, Maßstabsbalken: 50 µm).

es show a smooth transition to the neighbouring ones. Normally, the single crystal faces are distinguishable and a classification *sensu* Pupin (1980) is possible in most cases. Due to rounding, some smaller faces can be undistinguishable, but are often reconstructible using the remaining faces.

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7 Well rounded: Some edges and angles are rounded in a way that they are not recognisable anymore. Hence, the differentiation of some crystal faces is not possible. In some cases a classification *sensu* Pupin (1980) is possible, depending highly on the visibility and the arrangement of the crystal faces.

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8 Very well rounded: All edges and angles are very well rounded and not recognisable in larger parts, the classification *sensu* Pupin (1980) is not possible anymore.

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9 Almost completely rounded: Only few edges and angles are partially recognisable. Remains of crystal faces are visible in some cases, but differentiation and classification *sensu* Pupin (1980) are impossible.

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10 Completely rounded: There are no edges and angles anymore. Only few remains crystal faces are hardly recognisable in some cases. The classification *sensu* Pupin (1980) is impossible.

Table 2. Ratios and classification after Mitterer (2001) for both common possibilities of calculation of elongation.

Tabelle 2. Werte und Klassifikation nach Mitterer (2001) für beide gewöhnlich angewandten Möglichkeiten der Elongationsberechnung.

crystal habit	stubby		stalky		columnar or prismatic		needle-like
	short-	long-	short-	long-	short-	long-	
elongation (width/length)	1.0 – 0.67	< 0.67 – 0.50	< 0.50 – 0.40	< 0.40 – 0.33	< 0.33 – 0.25	< 0.25 – 0.17	< 0.17
elongation (length/width)	1.0 – 1.5	> 1.5 – 2.0	> 2.0 – 2.5	> 2.5 – 3.0	> 3.0 – 4.0	> 4.0 – 6.0	> 6.0

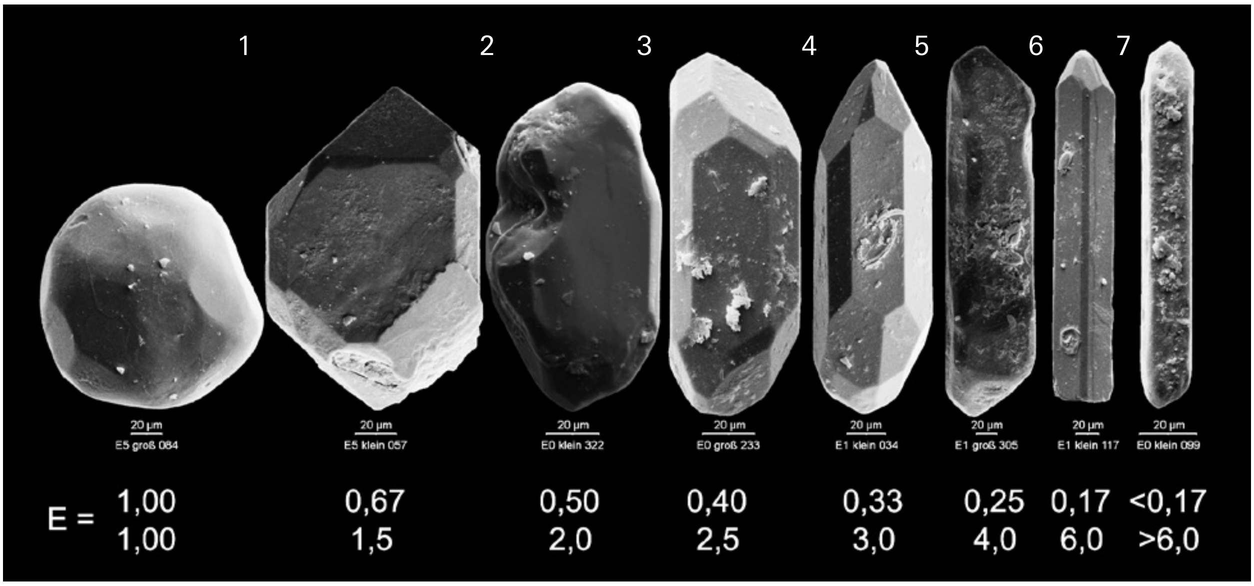

Fig. 2. The different classes of elongation exemplarily shown by characteristical grains representing the limiting values of each class (scale bar: 20 µm).

Abb. 2. Darstellung von charakteristischen Körnern der verschiedenen Elongationsklassen, welche jeweils die Grenzwerte der Klassen aufweisen (Maßstabsbalken: 20 µm).

3.2. Elongation

The ratio of width divided by length is to be termed as elongation, which is bounded by the minimum value of 0 and the maximum value of 1. Another possible ratio with changed dividend and divisor after Poldervaart (1955, 1956) is called elongation, too (List 1966). The two equations are reciprocal to each other, thus, the results are comparable. Both possibilities are used in literature (e.g. Blott & Pye 2008, Finger & Haunschmid 1988). Moreover, Wang (1998) uses a slightly different equation, which is not as common as the above mentioned possibilities. Among others, Mitterer (2001) utilises a seven-staged classification for morphological studies of zircons (Tab. 2, Fig. 2).

Former studies used elongation as an indicator for possible host rocks (e.g. Poldervaart 1955, 1956, Hoppe 1963, List 1966). For example, zircons of granitic origin usually are more elongated than zircons of sedimentary origin (Poldervaart 1955, 1956, Hoppe 1963, Finger & Haunschmid 1988). Furthermore, differences in zircon morphology are also observed within magmatic rocks, caused by their cooling rates. The faster cooling takes place, the more elongated are the zircons (Kostov 1973, Zimmerle 1975). Additionally, Finger & Haunschmid (1988) mention, that there is the possibility of presence of some subpopulations of inherited zircons with deviating elongations in various rocks.

For studies including sediments it is to consider that this parameter is conditioned by the distance of transport, because grains tend to be shorter within a longer way of transport (Wyatt 1954, Poldervaart 1956, Dietz 1973). Furthermore, there is a limited variability even within the host rocks (Hoppe 1962). Thus, the significance of elongation for provenance analyses is more or less restricted to the more elongated zircon grains and therefore this feature should be recorded, but not be over-interpreted.

3.3. Surface characteristics

Zircons show a widespread variety of surface characteristics like fracturing, cracks, scratches, striations, and impact pits all resulting from transport processes. Surface characteristics like impressions of other crystals or gas

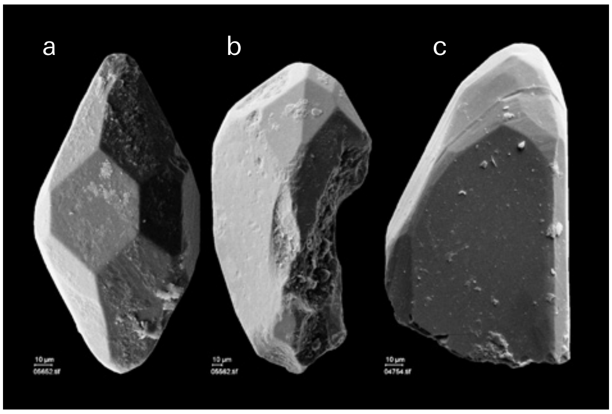

Fig. 3. Typical zircon grains representing the three classes of fracturing (**a** to **c**, scale bar: 10 µm).

Abb. 3. Typische Zirkonkörner der drei Bruchklassen (**a** bis **c**, Maßstabsbalken: 10 µm).

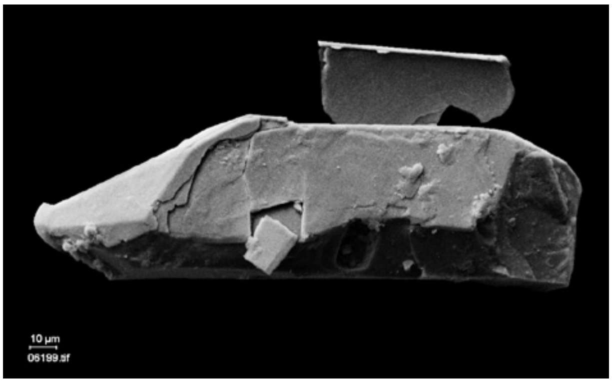

Fig. 4. *In situ* delamination (scale bar: 10 µm).

Abb. 4. *In situ* Schalenablösung (Maßstabsbalken: 10 µm).

bubbles, which are not overgrown, were formed during the phase of magmatic crystal growth (Hoppe 1962). According to this, the latter ones do not belong to the group of characteristics used for provenance analysis. However, they form weak points at the crystal surfaces.

3.3.1. Fracturing

Fracturing of zircon grains is controlled by the effective energy during the transport process and only possible in two directions: parallel or nearly perpendicular to the c-axis of the crystal (Fig. 3). Caused by geometry and structure (Rösler et al. 2006), predominant direction of fracturing is through the c-axis. Depending on the number of fractured grains, the sample is determined as mainly influenced by high or low energy of transport.

Resulting from the three described possibilities there are three classes of fractioning:

a Not fractured.

—

b Fractured parallel to c-axis.

—

c Fractured (nearly) perpendicular to the c-axis.

Where as roundness increases during the entire transport process, the detectability of fracturing decreases, caused by abrasion of breaking edges. This fact has to be kept in mind for distal sediments.

3.3.2. Cracks

Caused by concentric growth during crystallisation, magmatic zircons show lamination of U-rich and U-depleted zones (Nasdala et al. 2003). There have to be weaker bonding forces at the bounding surfaces than within the single zones. Otherwise delamination along these layers (Fig. 4) would not be explainable. Thus, lamination is indicated by cracks at the zircon surface, caused by collisions during transport (Kempe et al. 2004, Gärtner 2011). An other type of cracks, going through central parts of some grains, result from extension during heterogeneous metamictisation (e.g. Hutton 1950, Ramdohr 1960, Chakoumakos et al. 1987, Lee & Tromp 1995, Sláma et al. 2008) and do not indicate delamination. Both types can be distinguished by their character of occurrence in the zircon crystal by imaging polished grains (Fig. 5). Only the first type of cracks is suggested to reflect transport processes. For this attribute there is a simply qualitative classification:

i Grains without cracks on their surface.

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ii Grains with cracks on their surface.

3.3.3. Collision marks

The number of collisions during the entire transport process is indicated by the amount of impact pits, scratches, and striations at the surface of a crystal (Fig. 6). Therefore, these collision marks are presumably related to the kinetic energy within the transport system and occur first at the crystal edges. Further investigations on this topic are scheduled. Current classification is four-staged and based on the three-staged categorisation of Voggenreiter (1986):

I Grains without or only very few collision marks on the surface, all edges and crystal faces are smooth.

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II Grains with some collision marks on the surface, some parts of the edges and crystal faces show surface defects.

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III Grains with a medium amount of collision marks on the surface, there are some relicts of sharp edges or smooth crystal faces.

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IV Grains with numerous collision marks on the surface, almost the whole crystal looks roughened.

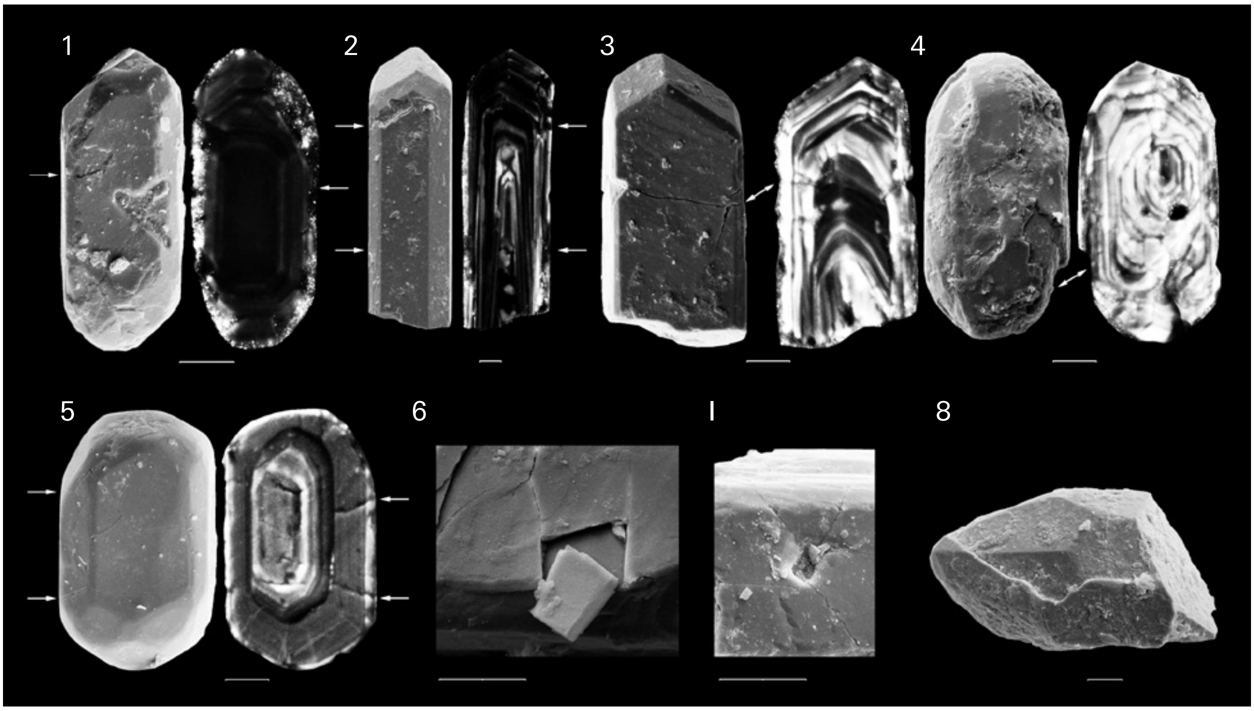

Fig. 5. The two different types of cracks in zircons: **1** and **2** are caused by collision during transport, **3** results from collision and from volume extension, **4** and **5** are caused by volume extension, **6** shows delamination of layers, **7** are cracks induced by collision, **8** is a zircon grain with partly removed outermost layer (scale bar: 20 µm).

Abb. 5. Die zwei Typen von Rissen in Zirkonen: **1** und **2** durch Kollisionen während des Transports verursachte Risse, **3** zeigt sowohl durch Kollision, als auch durch Volumenvergrößerung bedingte Risse, **4** und **5** sind aus Volumenvergrößerung resultierende Risse, **6** stellt Schalenablösung dar, **7** sind durch Kollision induzierte Risse, **8** zeigt einen Zirkon mit teilweise fehlender äußerster Schale (Maßstabsbalken: 20 µm).

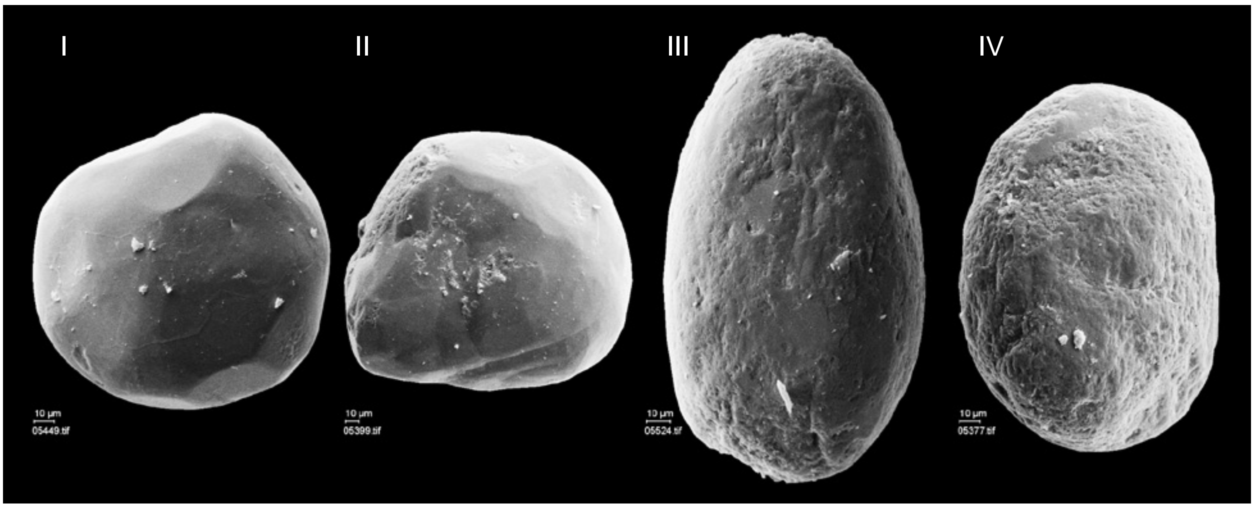

Fig. 6. Typical zircon grains of the four classes of collision marks (**I** to **IV**, scale bar: 10 µm).

Abb. 6. Typische Zirkonkörner der vier Klassen der Schlagmarken (**I** bis **IV**, Maßstabsbalken: 10 µm).

4. Illustration facilities of the data

Illustrating data is important for interpretation. In addition to two- or three-dimensional diagrams, which are mostly based on orthogonal coordinate systems or histograms (e.g. Fig. 7), there is a five-dimensional alternative. The spider plot shown in Fig. 8 contains information about roundness, collision marks, type of fraction, cracks at the crystal surface, and location. All given characteristics are replaceable against others, e.g. elongation. Thus, this plot provides the possibility to nicely illustrate the interrelations between some of the single characteristics within one diagram.

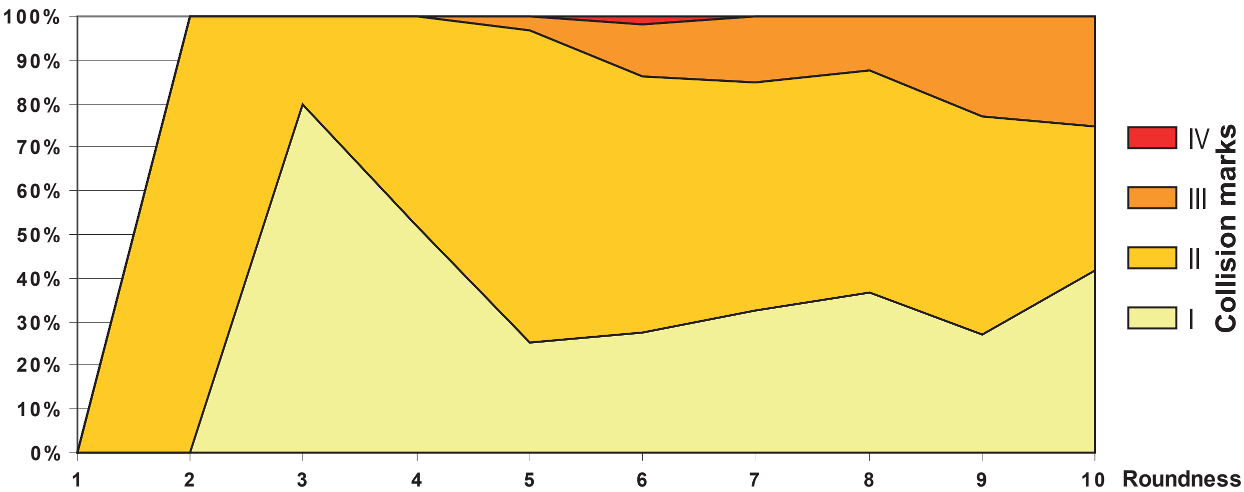

Fig. 7. Diagram illustrating the interrelation between roundness and collision marks for sample NAM-O-23 (Cunene River near Ruacaná, Namibia).

Abb. 7. Diagramm, das den Zusammenhang zwischen Rundheitsgrad und Schlagmarken für die Probe NAM-O-23 (Kunene bei Ruacaná, Namibia) illustriert.

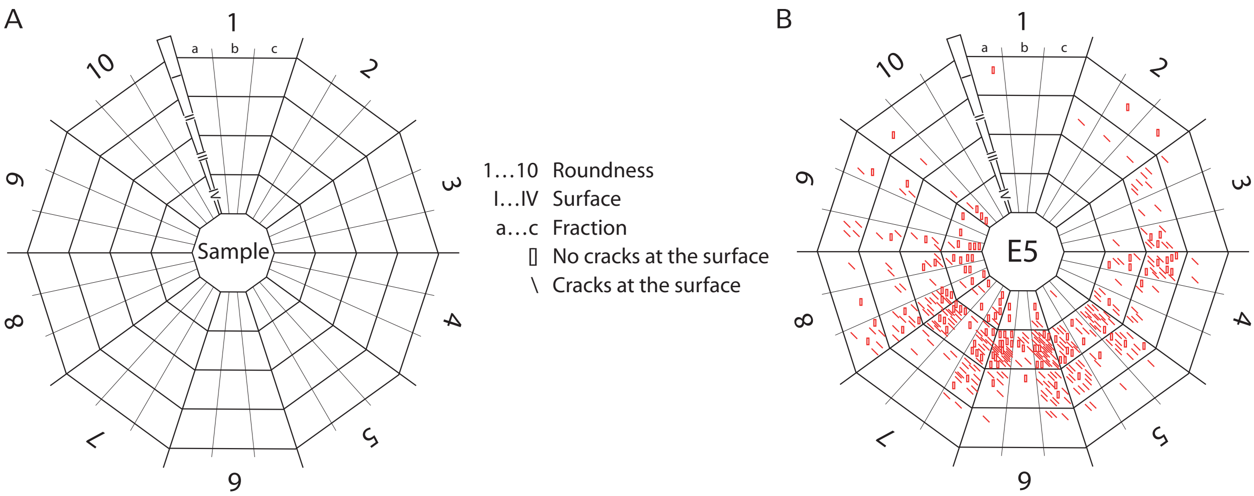

Fig. 8. Spider plot showing the interrelations between roundness, collision marks, type of fraction, cracks at the crystal surface, and location for sample E5 (Elbe River in Groß Schönebeck).

Abb. 8. Netzdiagramm, das die Zusammenhänge zwischen Rundheitsgrad, Schlagmarken, Bruchart, Rissen an der Kristalloberfläche und Lokalität für Probe E5 (Elbe in Groß Schönebeck) zeigt.

5. Conclusions

Detailed studies of zircon grains from sediments revealed various characteristics of their surfaces and shapes. In order to create a manageable guideline for further studies, definitions of characteristics were made. Hence, subdivision into three groups was essential:

1. Roundness with ten classes (1 to 10).

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2. Elongation with seven classes (1 to 7).

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3. Surface characteristics with three subgroups:
- **a** Fracturing with three classes (a to c).
- **b** Cracks at the surface of the crystal with two classes (i and ii).
- **c** Collision marks with four classes (I to IV).

Based on these defined classes, comparable studies of zircons from sediments are possible. Feasible illustration facilities are given by a multidimensional spider plot for zircon grain characteristics or common two- or three-dimensional diagrams, respectively. Nevertheless, further investigations on this topic are needed if all characteristics of sedimentary transported zircons shall be detected and interpreted.

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